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REGIONAL STRUCTURE, TECTONICS, AND BEDROCK GEOLOGY

Tectonic Evolution of the Death Valley Region

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INTRODUCTION

Progress in understanding the evolution of continents hinges on seamlessly applying techniques of modern structural geology to the largest possible regions of the crust. In most areas, meaningful practice of regional structural geology is limited by a lack of correspondence between highly strained crust and well-defined regional strain markers, that is, large-scale geologic features whose initial geometry can be reasonably inferred, and their kinematic evolution constrained, through structural, stratigraphic, isotopic, paleomagnetic, and geodetic study.

A ~100,000-km^2 segment of the U.S. Cordilleran orogen, encompassing the celebrated landscapes of Death Valley National Park and five nearby parks that are among the most visited in the U.S., was severely deformed in late Cenozoic time. In addition to spectacular geologic exposures, the region harbors a rare endowment of regional structural markers, developed before and during late Cenozoic deformation. The markers are defined by isopachs and facies boundaries in the west-thickening Neoproterozoic-Paleozoic Cordilleran miogeocline, by pre-Cenozoic thrust faults that disrupt the miogeoclinal wedge, and by proximal Tertiary terrigenous detrital strata and their source regions. The region is still tectonically active, providing an opportunity to compare deformation patterns of the last decade, constrained by geodetic studies, with late Cenozoic deformation patterns spanning 15–20 m.y.

These scientific assets have attracted the attention of significant numbers of structural geologists over the last three decades, and distinguished the region as the birthplace of, and testing ground for, an impressive number of fundamental tectonic ideas. Oroclinal bending of mountain ranges, continental transform faulting and "pull-apart" basins, low-angle normal faulting, the influence of plate motions on intracontinental deformation, the "rolling hinge" model of progressive extensional deformation, the fluid crustal layer or "crustal asthenosphere" concept, and Pratt isostatic compensation of mountain ranges were all originally discovered or have their best known expressions in the region. This remarkable history of geologic investigation and innovation continues unabated as growing numbers of scientists recognize it as a unique place on Earth to ponder the nature and origin of large-scale continental deformation.

METHODS AND SCOPE OF RESEARCH

The author's research program in this region began with his doctoral research in 1979 at MIT, mapping in the Mormon Mountains of southern Nevada under the supervision of B.C. Burchfiel. After joining the professoriate in 1982, my research program expanded to include most of the area from the Sierra to the Colorado Plateau, funded primarily by the Tectonics and Continental Dynamics programs in the Earth Sciences Division of the National Science Foundation, with important contributions from the Department of Energy, Nuclear Regulatory Commission, a consortium of energy companies, and university funds. It has included geologic mapping and structural analysis, stratigraphic studies, isotopic studies, paleomagnetic studies, geodetic studies, and participation in two major seismic experiments, the Southern Sierra Continental Dynamics (SSCD) Project and the Basin and Range Geoscientific Experiment (BARGE). A bibliography of the group's work relating to Basin and Range tectonics, including 53 published research papers, 4 abstracts of papers in preparation, 8 discussion papers, 6 field trip guidebooks and 8 theses, is presented at the close of this paper.

Mapping and structural analysis. Bedrock geologic mapping by the group totals some 3,300 km^2 at field scales ranging from 1:10,000 to 1:24,000 (fig. 1). It includes 2,000 km^2 between the Spring Mountains and Sierra Nevada (Death Valley extensional domain) and another 1,300 km^2 east of the Spring Mountains (Lake Mead extensional domain). In the Death Valley domain, the group has mapped (1) the Panamint Range from Stovepipe Wells to Harrisburg Flats (Hodges and others, 1987; Wernicke and others, 1993); (2) the central Resting Spring Range (Niemi and others, in press; Wernicke, unpublished); (3) the Cottonwood Mountains north of Hunter Mountain (Snow, 1990 and unpublished); (4) the central Black Mountains (Holm, 1992); (5) the northwestern Spring Mountains (Abolins, 1998); and (6) the Grapevine Mountains between Scotty's Castle and Titus Canyon (N. Niemi, Ph. D. thesis in progress). In the Lake Mead domain, mapping has included (1) most of the South

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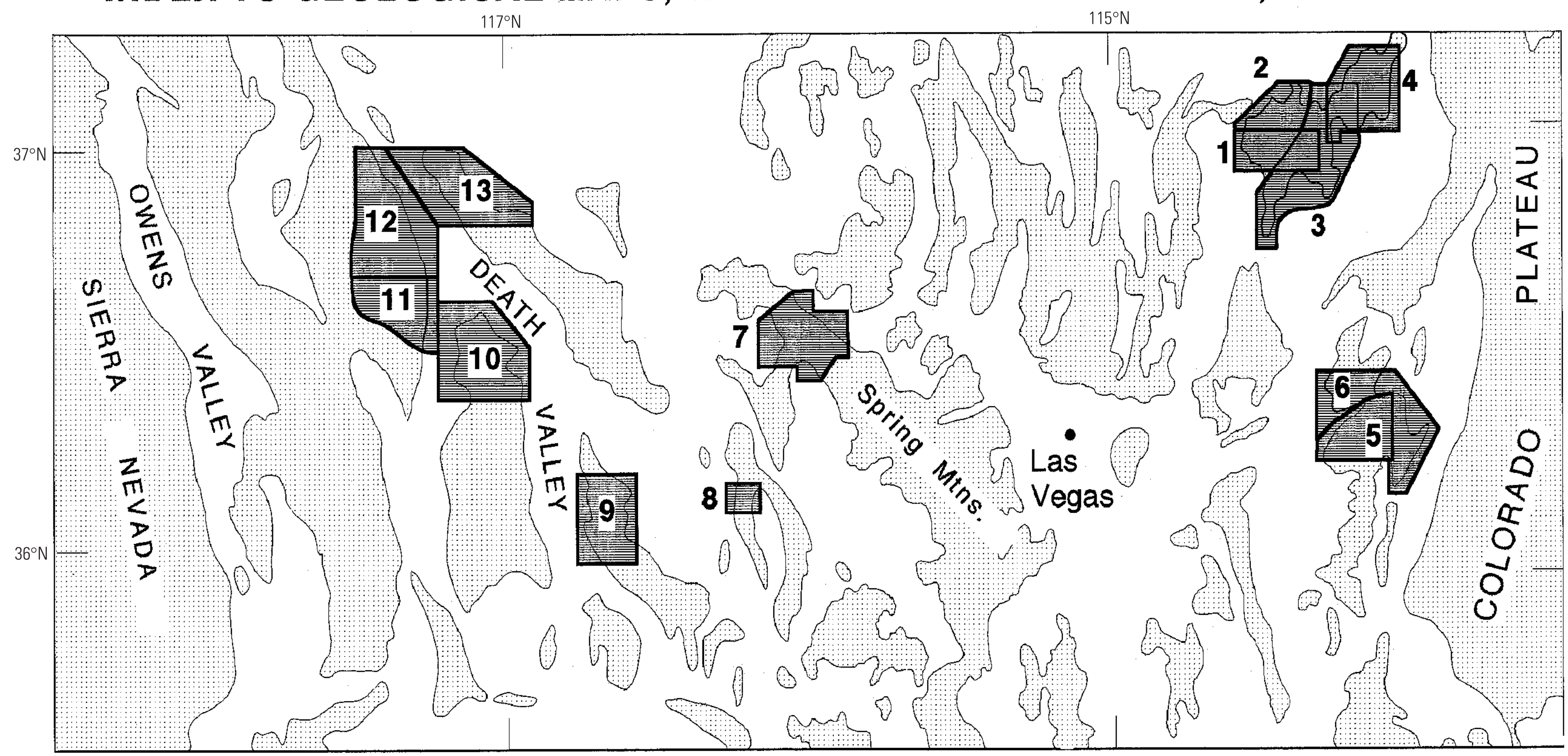

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Figure 1. Geologic mapping of the Wernicke research group, full references in bibliography at close of paper.

Virgin Mountains (Fryxell and others, 1992; Brady and others, in press); (2) the Mormon Mountains (Wernicke and others, 1985; Axen and others, 1990; Wernicke and others, 1984, unpublished); and (3) the Tule Springs Hills (Axen, 1993).

Stratigraphy. Detailed stratigraphic studies have been focused primarily on Oligocene and younger strata deposited prior to and during major Cenozoic deformation, and on key portions of the pre-Cenozoic miogeoclinal prism. From oldest strata to youngest, these studies have included (1) sequence analysis of the Neoproterozoic Johnnie Formation (Charlton and others, 1997; Abolins, 1998); (2) paleoflow directions in Eocambrian strata (Snow and Prave, 1994); (3) studies of the orientation of facies boundaries and isopachs in Paleozoic strata (Snow, 1992); and (4) measured sections, facies analyses, and paleoflow directions for Tertiary strata in the Cottonwood, Grapevine, and Funeral Mountains (Snow and White, 1990; Snow and Lux, in press), Black Mountains (Holm and others, 1994), and Resting Spring Range (Niemi and others, in press).

Geochronology, thermochronology and thermobarometry. Isotopic and petrologic studies, in collaboration with S. Bowring and K. Hodges (MIT), D. DePaolo (Berkeley), R. Dokka (LSU), P. Fitzgerald (Arizona), K. Farley and J. Saleeby (Caltech), S. Jacobsen (Harvard), D. Lux (Maine), and J. Selverstone (New Mexico) have included (1) cooling history and paleobarometric studies of the South Virgin Mountains (Fitzgerald and others, 1991; Brady, 1998; P. Reiners, unpublished data), Spring Mountains and Panamint Mountains (Wernicke and Dokka, unpublished data), Nopah Range (Wernicke and Farley, work in progress), Funeral Mountains (Holm and Dokka, 1991), Black Mountains (Holm and Wernicke, 1990; Holm and others, 1992; Holm and Dokka, 1993), northern Snake Range (Lewis and others, 1999), Skagit River area (Wernicke and Getty, 1997) and central Sierra Nevada (House and others, 1997, 1998); (2) intrusive and eruptive age determinations of igneous rocks in the South Virgin Mountains (Brady, 1998), Black Mountains (Asmerom and others, 1990; Holm and others, 1994), Resting Spring Range (Niemi and others, in press) and Cottonwood Mountains (Snow and others, 1991; Snow and Lux, in press; Niemi and others, in press); and (3) tracer studies targeted at understanding the evolution of source regions of magmas in the central Death Valley volcanic field (Asmerom and others, 1990, 1994). These studies include isotopic and nuclear-track age determinations on a total of 237 mineral separates, using the $^{40}Ar/^{39}Ar$ (68 separates), (U-Th)/He (85 separates), fission-track (61 separates), U/Pb (16 separates) and Sm/Nd (7 separates) systems.

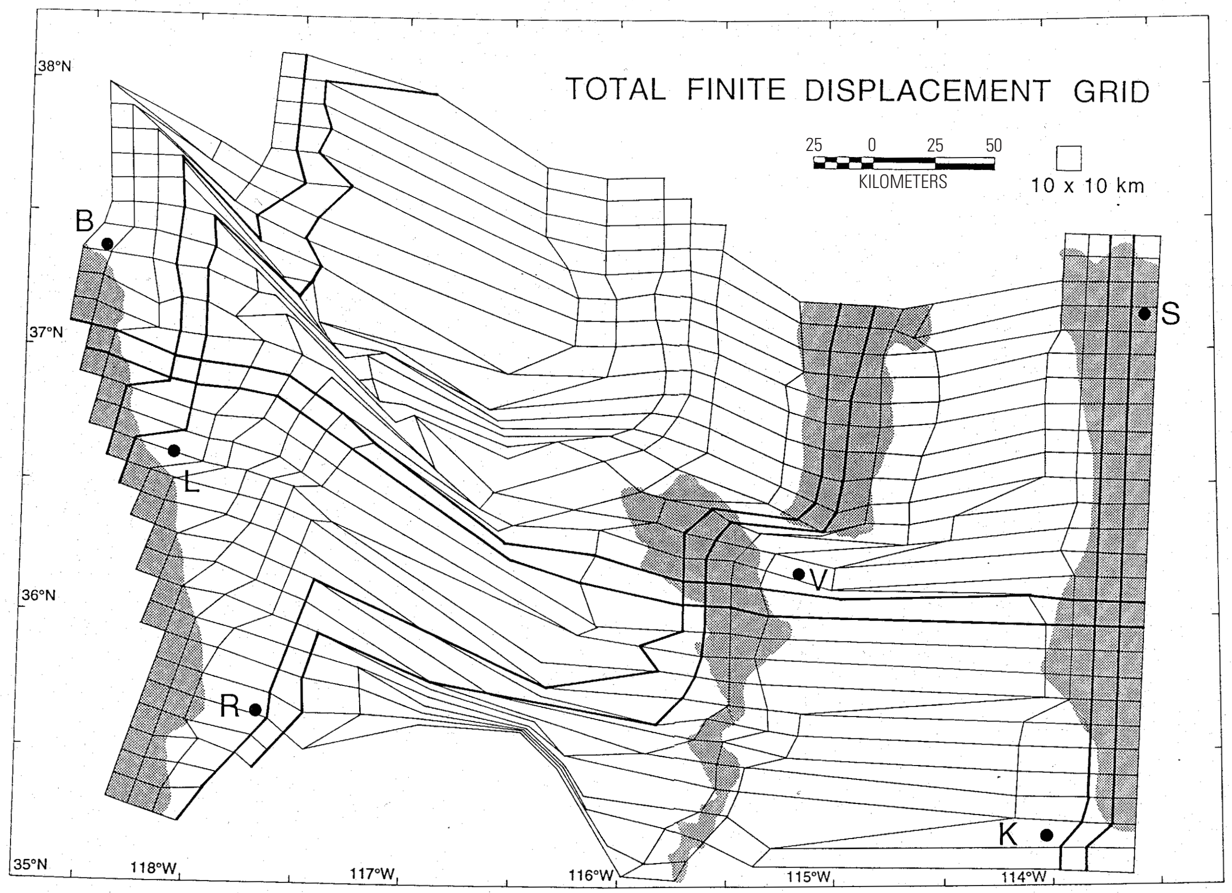
Paleomagnetism. Paleomagnetic studies in collaboration with J. Geissman (New Mexico) have been aimed at unraveling the complex vertical-axis rotation histories of critical range blocks. To date, we have sampled and analyzed more than 250 sites (about 2,300 sample cores), including (1) 75 sites in the South Virgin Mountains (Proterozoic and Mesozoic crystalline rocks; J. Geissman and others, unpublished data); (2) 54 sites in the Black Mountains (Miocene intrusions and mafic lavas; Holm and others, 1993; Petronis and others, 1997); (3) 47 sites in the Funeral and Grapevine Mountains (mainly Paleozoic carbonate and Tertiary volcanic strata; Snow and others, 1993); (4) 30 sites in the Panamint Mountains (Miocene intrusives, mafic lavas, and Paleozoic carbonates; Petronis and others, 1997); and (5) 50 sites in the Greenwater Range (Miocene intrusions and Miocene and younger volcanic strata; Petronis and others, 1997).

Geodesy and geophysics. In collaboration with J.L. Davis (Smithsonian Astrophysical Observatory), we have conducted annual campaign-style GPS geodetic surveys of a 15-site network in Death Valley National Park and the adjacent Yucca Mountain area since 1991 (Bennett and others, 1997; Wernicke and others, 1998a). Since 1996, we have been building a 50-site network of continuously operating GPS stations covering the entire Great Basin and adjacent portions of the Colorado Plateau and Sierra Nevada. The first 18 of these sites, primarily in the northern Great Basin, became operational in 1996 (Bennett and others, 1998; in press). The remaining 32 sites became operational in early 1999 (Wernicke and others, 1998b). Continuous sites include one site each in the Argus Range, Panamints, Funerals, Greenwaters, Dublin Hills, Bullfrog Hills, and Las Vegas Range; two each in the Sierra Nevada, Spring Mountains, and Grand Canyon area; and an additional 15 sites deployed across the southern part of the Nevada Test Site, centered on Yucca Mountain.

In September 1993, in collaboration with a large number of institutions, the group participated in the SSCD, which involved deploying 700 seismometers along an east-west seismic refraction line extending from Visalia to Death Valley Junction, and 2 days later reinstalling the same 700 seismometers along a north-south line from Bishop to the Ridgecrest area.

SUMMARY OF RESULTS

The results of our latest reconstruction (fig. 2, Snow and Wernicke, in press), which modifies an earlier reconstruction (Wernicke and others, 1988) by accounting for new stratigraphic, paleomagnetic and isotopic data, indicate ~250–300 km of west-northwest motion of the Sierra away from the Colorado Plateau since 20 Ma. Extension is balanced by both crustal thinning and north-south shortening of the intervening continental crust. Tertiary intermontane basin deposits and mineral cooling ages of deeply exhumed rocks constrain the overall kinematics, permitting the construction of a strain-compatible "movie" of range-block positions in 2-m.y. increments. This exercise revealed a strong component of westward migration of intense deformation with time,



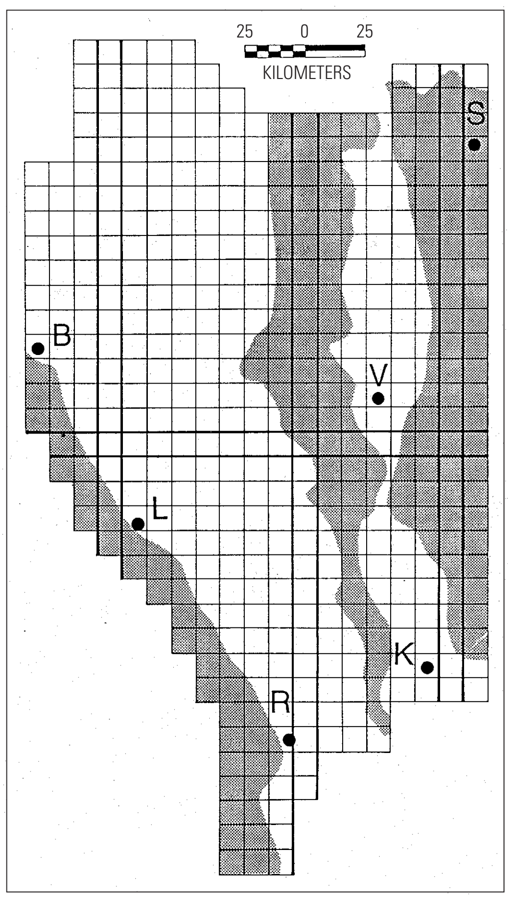


Figure 2 (above and left). Reconstruction of deformation, southern Great Basin region, modified from Snow and Wernicke (1999). Left, configuration at 36 Ma; above, present day configuration. B, Bishop; L, Lone Pine; R, Ridgecrest; V, Las Vegas; S, St. George; K, Kingman.

consistent with the "rolling hinge" model of extensional deformation (Wernicke and Axen, 1988; Wernicke, 1992; Holm and others, 1992; Holm and Dokka, 1993; see also Hoisch and others, 1997).

Kinematic interpretations of local subareas at significant variance with the Wernicke and others and Snow-Wernicke reconstructions include those of Anderson and others (1994) for the Lake Mead area, Caskey and Schweickert (1992) for the Nevada Test Site area, and Cemen and others (1985) and Serpa and Pavlis (1996) for the central Death Valley area. All kinematic models agree that significant extension has affected the crust, but they differ in the restored positions of range blocks and in the amounts of map-view shear, crustal shortening, and crustal thinning so derived. In the author's opinion, these models lack balanced consideration of the entire system of traceable strain markers, each realizing small gains in local simplicity in the face of huge losses in regional coherence, especially in regard to strain-compatible incremental restorations.

The restored positions of range blocks are not specified in the Anderson and others model for comparison with the

Snow-Wernicke model. However, their previously published cross sections through the Mormon Mountains–Tule Springs Hills area that attempt to minimize extension are grossly out-of-balance. Their conservative pre-Cenozoic positioning of the Spring Mountains relative to the Colorado Plateau fails to account for proximal fan breccias on the west side of the region derived from the South Virgin Mountains on the east side. Although we agree with their overall premise that the deformation pattern is complex, it is difficult to identify specific elements in their interpretations that preclude our model, and we therefore find their claims of variance with our model somewhat exaggerated and dificult to evaluate.

The Caskey-Schweickert model of thrust geometry in the Test Site area turns on sparsely exposed, relatively ambiguous structural relations in the Mine Mountain–CP Hills area. Alternative interpretations of this area lead to major differences in the geometry of pre-Cenozoic thrusts, and hence in how one correlates them with thrust to the south and west. Their preferred geometry and correlations do not significantly compromise the Snow-Wernicke reconstruction, which is based primarily on relations in the central Death Valley area. However, they do introduce improbable along-strike complexities in the pre-Cenozoic geometry of both the thrust belt and miogeoclinal stratigraphic trends.

The Cemen and others model calls for relatively modest extension across the central Death Valley region, based primarily on the distribution of middle and upper Miocene strata between the Panamints and the Resting Spring Range. In contrast, the Snow-Wernicke model (essentially the same as that of Stewart (1983) in this area) juxtaposes the Panamint and Resting Spring Ranges in order to align various pre-Cenozoic markers. As with the Caskey-Schweickert model, both the Cemen and others and Serpa-Pavlis models require a complex and improbable initial configuration of these markers. Even if such complexity is granted, both restorations leave proximal middle Miocene conglomerates in the Resting Spring Range stranded many tens of kilometers southeast of their source area in the southern Cottonwood Mountains. These conglomerates record multiple flooding events carrying detritus up to a meter in diameter that is derived entirely from rock types in the modern Marble Canyon drainage, now 105 km to the north-northwest (Niemi and others, 1999). These considerations and paleoflow data suggest that the conglomerates were deposited no more than 10–20 km north-northeast of their source, precluding both models. The comparative tectonic stasis of the central Death Valley area throughout the middle and late Miocene indicated by the Cemen-Wright model also precludes any reasonable explanation for the exhumation of the Black Mountains crystalline terrain from depths in excess of 10 km during the same interval (Asmerom and others, 1990; Holm and others, 1992; Holm and Dokka, 1993).

The principal feature of the Serpa-Pavlis model is a net clockwise rotation of the Panamints relative to the Funerals during deformation, such that the east side of the Panamints lay against the southwest margin of the Funerals, restoring the southern Panamints adjacent to the northern Resting Spring Range. The Serpa-Pavlis model does not take into account major range-parallel distension of the Funerals relative to the Panamints, which precludes their map-view reconstruction geometry and proposed correlations of pre-Cenozoic thrust faults. Further, the proposed relative range block rotations conflict with both paleomagnetic and paleoflow orientations measured in the Panamints and Funerals (Snow and Prave, 1994; Petronis and others, 1997). However, aspects of the Serpa-Pavlis model may provide a more plausible explanation than the Snow-Wernicke model for complex relations in the southern Death Valley area, where in any event regional strain markers are not well defined.

Based on our reconstruction (fig. 2), the motion of the Sierran block with respect to the Colorado Plateau was mainly westerly at more than 20 mm/yr from 16 to 10 Ma, changing to northwest or north-northwest since 8–10 Ma, at an average rate of 15 mm/yr (Wernicke and Snow, 1998). This overall kinematic reconstruction is consistent with two other independent methods of determining the position of the Sierran block since 20 Ma. These include (1) reconstructions based on paleomagnetic data from range blocks that bound the Basin and Range on the west (see L. Frei, 1986, *Geological Society of America Bulletin*); and (2) a revised history of Pacific-North America plate motion based on a global plate circuit (see T. Atwater and J. Stock, 1998, *International Geological Review*). The plate tectonic reconstruction shows a change to more northerly motion between the Pacific and North American plates at about 8 Ma, in concert with the motion of the Sierran–Great Valley block. Moreover, the northeast limit of extant oceanic crust (as indicated by the reconstruction of the continental geology) tracks closely with the southwest limit of extant continental crust (as indicated by the positions of oceanic plates) since 20 Ma. The coordination between plate motions and the intraplate geology implies that we have not grossly overestimated the amount of deformation in the Death Valley and Lake Mead regions; rather it strongly suggests that evolving plate boundary forces were a major influence on deformation within the continent.

The Snow-Wernicke reconstruction makes it possible to quantify the partitioning of strain between vertical crustal thinning (via normal faults), map-view plane strain (via conjugate strike-slip faults), and crustal shortening (via folds and thrust faults). Placing a grid of 10 km×10 km square elements on a retrodeformed map of the region, and measuring the increase in area of grid elements between the undeformed and present-day (Snow and Wernicke, in press), we obtain a maximum finite elongation of the Basin and Range at lat 36°–37° N. of 3.4, oriented N. 73° W. (fig. 2).

Map-view area balance shows that 20 percent of this elongation is accommodated by map-view plane strain, and 80 percent by crustal thinning. This yields an average thinning factor for the upper crust of 2.7 between the Sierra and Plateau, consistent with values suggested previously (Wernicke and others, 1988) and precluding the hypothesis that overall Neogene deformation in the central Basin and Range is predominantly dextral shear plane strain.

The contemporary strain field, however, as revealed by GPS studies, is clearly dominated by regional right shear (Bennett and others, 1997; in press). The extreme localized thinning of the upper crust, in concert with seismic data showing that the southern Sierra Nevada has similar crustal thickness to the central Basin and Range (Wernicke and others, 1996), supports the hypothesis of large-scale eastward flow of Sierran deep crust during extension, as a fluid layer or crustal asthenosphere (Wernicke, 1990, 1992; Wernicke and Getty, 1997).

ROLE OF THE NATIONAL PARK SERVICE IN RESEARCH

During the last 20 years, support for geologic research in the region by the National Park Service and other agencies has generally been strong. Recently, however, in Death Valley National Park in particular, relations between scientists and park managers and patrol rangers have deteriorated significantly. The root of the problem may lie in intensifying demands on the Park Service by Congress, various public interest groups (assuming you're part of their particular public), and possibly even the public itself, without commensurate increases in Federal support. These changes may have promoted misunderstanding on the part of both park managers and researchers as to one another's objectives and concerns.

Researchers perceive a heightened bureaucratic workload unilaterally imposed on them by park managers, and are skeptical that these efforts are of significant benefit to either science or protection of park resources. Based on a formal poll of scientists working in the park, newly instituted permitting and reporting requirements (outlined in *Information for Researchers*, 1995) are variously regarded as unrealistic, excessively bureaucratic, obstructive, out-of-step with the needs of the research community, or all of the above. Despite the official encouragement of research by the park, in practice most researchers complain of an unwelcoming atmosphere and distrust from resource managers and outright hostility from patrol rangers, and believe that substantial damage to the park's scientific mission is being done. Accordingly, these procedures require careful reevaluation by the park. A local task force, perhaps including both researchers and park managers, should be formed to air concerns and establish a new set of permitting and reporting procedures, perhaps more along the lines of those in place prior to 1995.

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[T] Tectonic analysis
[S] Stratigraphy
[C] Geochemistry (geochronology, thermochronology, thermobarometry)
[G] Geophysics (paleomagnetism and seismology)
[N] Neotectonics (geodesy)

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